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Electro-thermal model of DC Flashover discharge of Polluted Insulator

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Abstract: This paper is aimed at the presentation of electro-thermal mathematical model for the calculation of flashover critical voltage (V_{cri}) and critical current (I_{cri}) of polluted insulator. The used model integrates a particular solution of Elenbaas-Heller equation that has been proposed by Frank-Kamenetski. It also takes into account the pollution resistance and the temperature of the discharge. Different types of electrolytes are also investigated. The I_{cri} and V_{cri} computed using the relationships we established are found in a good accordance with the experimental ones and the temperatures of the discharge channel deduced from this model are closer to those reported in literature. It also appears from this study that the most important components of the discharge column are water vapour and air is a good approximation; the transfer of metal ions does not have any significant influence.

1 INTRODUCTION

The pollutant deposits covering the insulating surfaces can engender a considerable decrease of the dielectric strength of the systems which can lead to flashovers [1]. Due to the implication of many parameters (nature of insulator material, insulator profile, contamination layers including the type of contaminants and their distribution, atmospheric conditions ...) in this decrease, the elaboration of mathematical models that can help in the choice of appropriate insulators (form, dimensions, material ...) enabling to ensure a good service of the electro-energetic systems avoiding the dangerous effects induced by the insulators flashover is not an easy task [2-6].

Among the phenomena that influence the flashover of insulators, the drying of some parts of the pollution layer in the case of wetted layers resulting of the local heating induced by the leakage currents and partial discharges. Also, very high temperatures can have a destructive effect on polymeric insulators [7-9]. Thus, the knowledge of the temperature of discharge channel is an indicating parameter that can help to avoid dramatic situations for the transmission line. Most of the works reported in literature don't give indication about the temperature of discharge channel and consider this one as an arc discharge.

The aim of this paper is the presentation of electro-thermal mathematical model for the calculation of critical flashover voltage (V_{cri}) and critical current (I_{cri}) of polluted insulator. The model takes into account the discharge temperature, the resistivity of the pollution

layer, shape and polarity of the applied voltage. Different types of electrolytes are also investigated.

2 ELECTRO-THERMAL MODEL

The commonly equation of pollution flashover used by many authors is based on the Obenaus model [2, 12] that is defined by

$$U_{app} - V_{an} - V_{ca} = V = XNI^{-n} + R_p(X)I \quad (1)$$

where V_{an} and V_{ca} are the discharge voltage drops at the anode and cathode respectively; $V_{cr}(X)$ is the voltage at the discharge channel and I is the leakage current. The voltage drop at the electrodes can be considered as constant [2] and can be ignored in the calculations of critical conditions. N and n are the discharge characteristic constants that depend upon the environment (i.e., the experimental conditions) in which the arc is burning, the chemical constitution of the pollution layer and the polarity of the applied voltage [2, 11-14]. And $R_p(X)$ represents the unabridged part of the pollution layer

$$R_p(X) = \frac{\rho_p}{s_p}(L - X) = r_p(L - X) \quad (2)$$

ρ_p is the pollution layer resistivity, s_p is the cross section of pollution layer, r_p is the linear resistance of pollution layer and L is the total leakage length of insulator.

The critical parameters (i.e., critical length, current and voltage) are estimated using the following equations [2-4, 11-14]

$$X_{cri} = \frac{L}{n+1} \quad (3)$$

$$I_{cri} = \left(\frac{N}{r_p} \right)^{1/n+1} \quad (4)$$

$$V_{cri} = L N^{1/n+1} \cdot r_p^{n/n+1} \quad (5)$$

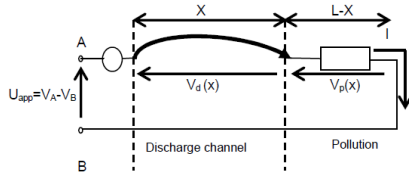


Figure 1. Model of discharge in series with an electrolyte according to Obenaus [10]

In previous work [4, 14], we presented a mathematical model of critical parameter of flashover discharge based on RLC model (Figure 2).

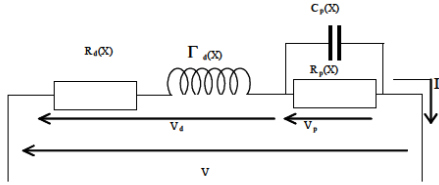


Figure 2. Equivalent electrical circuit RLC

The electrical equation that describes this model is

$$V = R_d(X)I + j\omega\Gamma_d(X)I + \frac{R_p(X)}{1 + j\omega R_p(X)C_p(X)}I \quad (6)$$

where Z_d , R_d and Γ_d are respectively the impedance, the resistance and the inductance of discharge channel; Z_p , R_p and C_p are respectively the impedance, the resistance and the capacitance of polluted layer; ω is the pulsation ($\omega = 2\pi f$, f being the frequency). The polluted layer is represented by R_p in parallel with C_p and

$$R_d(X) = r_d X = X \frac{\rho_d}{s_d}; \quad R_p(X) = r_p(L - X) = \frac{\rho_p}{s_p}(L - X)$$

$$\Gamma_d(X) = l_d(X); \quad C_p(X) = \frac{c_p}{L - X} = \epsilon_p \frac{s_p}{L - X}$$

where r_d , ρ_d and l_d are respectively the linear resistance, the resistivity and the linear inductance of discharge channel; s_d is the cross section of the discharge channel; c_p is the linear capacitance of polluted layer.

According to Dhahbi *et al* [3], the discharge instability condition is such as

$$\frac{d|Z_{eq}|^2}{dX} \leq 0 \quad (7)$$

Z_{eq} is the equivalent impedance of the system given in Figure 1.

This leads to define the discharge length on DC case

$$X_{cri} = \frac{L}{1+k} \quad (8)$$

and

$$n_{DC} = k = \frac{r_d}{r_p} \leq 1 \quad (9)$$

On other hand, for an arc burning in air and water vapour at atmospheric pressure, radiation losses are small and the majority of the electrical dissipation heats the surrounding gas [2 - 4, 6, 14, 16]. The heat transfer balance equation of arc is derived according to Elenbaas–Heller model [15]

$$\frac{1}{a} \frac{d}{da} \left[a\lambda(T) \frac{dT}{da} \right] + \sigma(T) E^2 = 0 \quad (10)$$

where a is the arc radius, T is the axial temperature required to provide the necessary amount of thermal ionisation, $\sigma(T)$ is the arc conductivity and E the electric field within the arc channel.

The arc conductivity is function of temperature according to [4, 16-19]

$$\sigma(T) = \sigma_0 \exp\left(\frac{-W_i}{2K_B T}\right) \quad (12)$$

where σ_0 is a constant in the range of operating temperatures of the arc. W_i represents the first ionization energy of the different species constituting the discharge channel; K_B is the Boltzmann constant.

Several analytical methods for solving equation (12) have previously been presented. According to the solution proposed by Frank-Kamenetski [16, 17], the energy dissipated by thermal conduction within the arc channel is

$$P_d = (4\pi T)^2 \lambda(T) \frac{K_B}{W_i} \quad (13)$$

According to references [18, 19, 21], the presence of metallic ion in the discharge column doesn't have a significant effect on the discharge critical voltage; and the most important chemical species that probably have an important role on the flashover voltage are water vapour and air. Then, one gets an approximate value $\lambda(T)$ as [20]

$$\lambda(T) = \lambda_{av} = \sum_{i=a}^v \frac{\lambda_i}{1 + \frac{A_i(1-v_i)}{v_i}} \quad (14)$$

where λ_i , v_i and A_i are the thermal conductivity, volume fraction and kinetic gas coefficient, respectively for each constituent; indexes a and v are related to air and water vapour respectively. The term λ_i depends on temperature and the species constituting the discharge column.

In previous work [4, 14], we showed that the characteristic constant N can be written as

$$N = r_d \left(\frac{P_d}{r_d} \right)^{\frac{1+k}{2}} \quad (15)$$

Then, we can deduce the relationships of critical current and critical voltage as

$$I_{cri} = (k)^{\frac{1}{k+1}} \cdot \sqrt{\frac{P_d}{kr_p}} \quad (16)$$

$$V_{cri} = L \cdot (k)^{\frac{1}{k+1}} \cdot \sqrt{\frac{r_p \cdot P_d}{k}} \quad (17)$$

where P_d is deduced from equation (13).

3. VALIDATION OF THE MODEL

The different parameters of the discharge are computed in an interval of temperature corresponding to a transitional glow to arc discharge: $1000 < T < 6000$ [17, 19]. To validate our model, we use the experimental results presented in previous work [4, 18, 21] for positive DC voltage (Table 1).

Table 1: Considered electrolytes

Electrolyte	Constitution
Pollution 1	$NaCl + H_2O$
Pollution 2	$KCl + H_2O$
Pollution 3	$CuSO_4 + H_2O$
Pollution 4	$Na_2CO_3 + H_2O$

3.1 Critical voltage and critical current

Figures 3 and 4 show the variations of experimental and computed values of critical voltage and current (equations (16) and (17)) versus the linear resistance of pollution deposit for different pollutions. We observe a good agreement between both experimental and computed critical parameters. When increasing the pollution linear resistance, the critical flashover voltage increases and the critical current decreases.

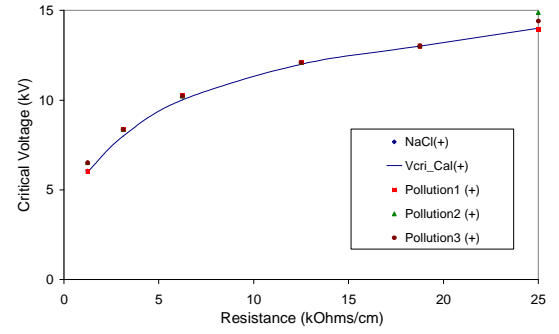


Figure 3. Comparison of calculated and measured critical voltage versus the linear resistance of pollution

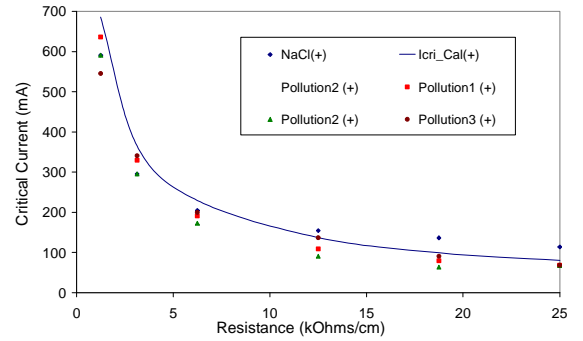


Figure 4. Comparison of calculated and measured critical current versus the linear resistance of pollution

3.2 Physical parameter of the discharge

Figures 5 and 6 show the computed variations of the linear resistance of discharge, the electrical discharge gradient and the current versus the discharge temperature.

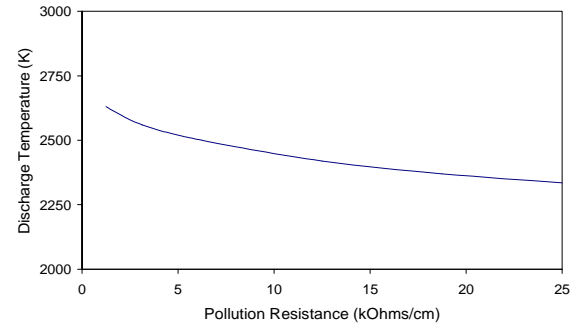


Figure 5. Variation of discharge temperature versus the linear resistance of pollution

We note that the critical current and the power loss of the discharge increase with the temperature, while the resistance of the discharge channel decreases. This result reflects the phenomenon of progressive thermalization of the discharge with the increasing values of pollution resistance. According to our calculations, the temperature of discharge

corresponding to critical conditions varies between 2300 K and 2650 K when the point is positive. These temperatures are closer to the temperature reported in literature [8, 15 and 17].

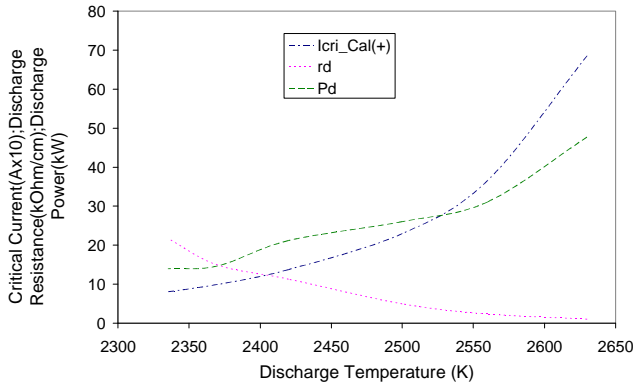


Figure 6. Variation of critical current, discharge resistance and discharge power versus the linear resistance of pollution.

4. CONCLUSION

The critical voltages and critical current computed using the proposed model we established elsewhere are found in a good accordance with the experimental ones. This work shows that the type of salt don't have a significant influence on critical parameters. It also appears that the most important components of the discharge column are water vapour and air; and the transfer of metallic ion has not a significant influence on calculation. The result reflects the phenomenon of progressive thermalization of the discharge with the increasing values of pollution resistance.

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